Conjugate Gradient Algorithm with Edge-Preserving Regularization for Image Reconstruction from Ipswich Data for Mystery Objects

P. Lobel[1], Ch. Pichot[2], L. Blanc-Féraud[1] , and M. Barlaud[1]

[1]Laboratoire Informatique Signaux et Systèmes de Sophia Antipolis
Bât. 4, 250 rue Albert Einstein 06560 Valbonne, France
E-mails : lobel@alto.unice.fr, blanc@alto.unice.fr, barlaud@alto.unice.fr
[2]Laboratoire d'Électronique, Antennes et Télécommunications, CNRS / Université de
Nice-Sophia Antipolis, Bât. 4, 250 rue Albert Einstein, Sophia Antipolis, 06560 Valbonne, France
E-mail : pichot@alto.unice.fr

1. Introduction

The reconstruction of the complex permittivity profile of 2D-TM objects using scattered far-field data is considered. In order to solve this nonlinear and ill-posed inverse scattering problem, an iterative algorithm based on a Conjugate Gradient (CG) method was proposed [1]. The formulation of the problem is given in terms of the minimization of a cost functional matching the measured scattered data with the computed ones. Then a Polak-Ribière CG direction is used for solving the problem. The algorithm was successfully applied on two Ipswich data sets, i.e. a metallic circular cylinder and a metallic strip [1,2].

In order to enhance the reconstruction in terms of stability of the algorithm with respect to noise, a regularized form of the CG method is now proposed and applied to a new Ipswich data set. The new scheme makes use of an *a priori* information on the object which is modeled with homogeneous areas separated by borderlike discontinuities. The regularization term, added to the cost functional, is based on Markov Random Fields potential functions [3,4] and allows a smoothing of the homogeneous areas while discontinuities are preserved.

2. Conjugate Gradient algorithm with Edge-Preserving (EP) regularization

We note C the complex image of the contrast (discretized in N elementary square cells) and $J(C)$ the error matching the measured scattered field E^S and the computed one $\rho(C)$

$$J(C) = \left\| E^S - \rho(C) \right\|^2 \tag{1}$$

where ρ is nonlinear in C. This nonlinear functional J is minimized using a CG method with the iterative sequence on C [1,2]

$$C^{i+1} = C^i + \alpha^i d^i \tag{2}$$

where α^i is the weighting parameter and d^i the Polak-Ribière CG direction [1]. In order to enhance the stability of the solution with respect to noisy corrupted data, we propose to introduce an EP regularization scheme as described in [5]. The solution is given by minimizing the new cost functional

$$J_R(C, b_R, b_I) = J(C) + J_{EP}(C, b_R, b_I) \tag{3}$$

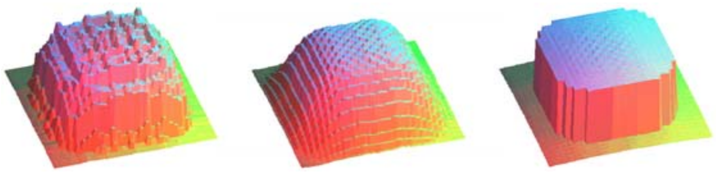
where $J_{EP}(C, b_R, b_I)$ is the regularization term defined as [3,5,6] :

$$\begin{aligned} J_{EP}(C, b_R, b_I) = {} & \lambda_R^2 \sum_{n=1}^{N} (b_R)_n \frac{\left\| \mathrm{Re}(\nabla C)_n \right\|}{\delta_R} + \psi\big((b_R)_n\big) \\ & + \lambda_I^2 \sum_{n=1}^{N} (b_I)_n \frac{\left\| \mathrm{Im}(\nabla C)_n \right\|}{\delta_I} + \psi\big((b_I)_n\big) \end{aligned} \tag{4}$$

The weighting parameters λ_R and λ_I fix the influence of the regularization term versus the error matching the scattered field, and the parameters δ_R and δ_I fix the threshold level on the gradient norm above which a discontinuity is preserved and under which it is smoothed. The two matrices b_R and b_I map the discontinuities (edges) respectively of the real and the imaginary part of the contrast, such as small gradients are smoothed while high gradients are preserved. As proposed in [3,5], an alternate minimization of J_R is used : with C fixed, the optimum values of b_R and b_I are analytically obtained, and with b_R and b_I fixed, the CG method proposed in [1,2] is applied on J_R.

3. Reconstructions from Ipswich data

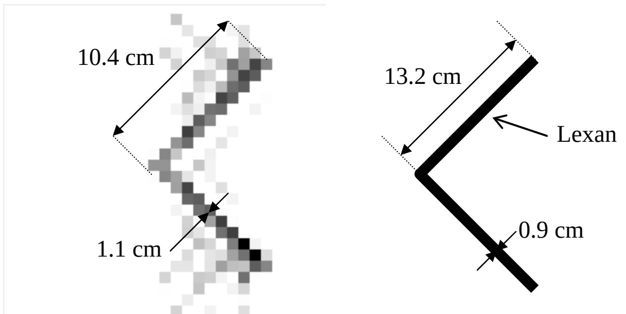
The measurements have been made in an anechoic chamber, using the swept-bistatic system at 10 GHz described in [7]. In order to match the experimental data with the simulated one, an amplitude and phase correction must also be applied on the data set. The complex calibration factor can be calculated in case of known objects in function of the measured scattered field and the simulated one [5]. In case of mystery objects, several blind tests must be applied in order to find a suitable calibration factor. In the following results, we used a zero contrast initial guess. In order to test the inversion algorithm, a known dielectric target has been investigated. It was a lossless polystyrene square cylinder with $\varepsilon_r = 1.03$ and side equal to 11.2 cm^2. We use a domain D divided into 29×29 subsquares of 5.3 mm^2. The scattered fields were collected for six incident angles $\theta_I \in$ {0°,60°,120°,180°, 240°,300°}, over an observation sector $\theta_I + 180° \le \theta_S \le \theta_I + 375°$, with a sample spacing $\Delta\theta_S = 0.5°$. Using an *a priori* information about the geometry of the target, we symmetrize the object during the iterative reconstruction. A comparative study has been made in Fig. 1 on results obtained at the same degree of convergence without any regularization, with a Tikhonov (TK) regularization and with our EP regularization scheme. The reconstruction without regularization, shows a blurred profile with a coarse shape description. The use of a TK regularization smoothes the profile and the edges are not preserved. The new regularization scheme improves the performance of the CG algorithm : the edges are clearly preserved while the homogeneous areas are smoothed.



Without regularization TK regularization EP regularization

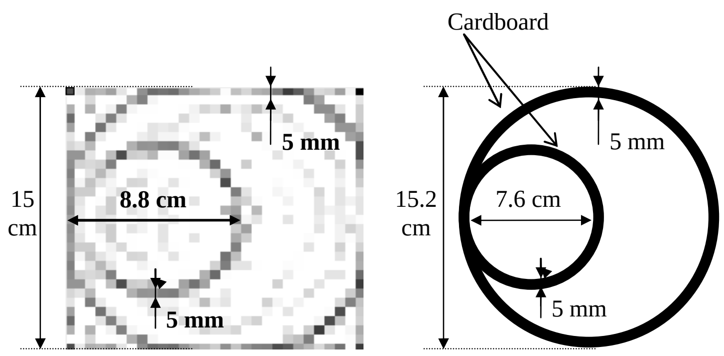
Fig. 1. Contrast profile of a square polystyrene object

We proposed then two other results obtained from two mystery objects named *ips005* and *ips007*. The scattered fields were collected from 36 view angles $\theta_I \in [0°,350°]$ with sample spacing 10°, over the observation sector $\theta_I \le \theta_S \le \theta_I + 170°$, with sample spacing $\Delta\theta_S = 10°$. The only one information given with these data sets is the radius of the minimum circumscribing circle. We show in Fig. 2 and Fig. 3 the results obtained by using the CG algorithm without any regularization (no *a priori* where used), and also the corresponding original profiles revealed at *the IEEE AP-S'96 Symposium* . The domain D is discretized into 29×29 square cells of 1 mm^2 for target *ips005* and 0.5 mm^2 for target *ips007*. The main problem was to find a satisfying calibration factor for each mystery targets. After several blind tests, we were able to propose two suitable reconstructions, using valid but non optimum calibration parameters. These reconstructions give a quite good spatial resolution of the two mystery objects.



Experimental reconstruction (200 iterations) Original profile

Fig. 2. Contrast profile of the mysterious target *ips005*



Experimental reconstruction (200 iterations) Original profile

Fig. 3. Contrast profile of the mysterious target *ips007*

4. Conclusion

This paper presents some evidence of the effectiveness of adding the EP regularization to the CG method in reconstructing the shape and permittivity profile of a dielectric objects. Without any *a priori* information, our CG algorithm is also still efficient and succeed in reconstructing two mystery targets. As the two targets are now known, we hope we can enhance greatly the reconstructions quality by choosing better values for the calibration factors and by applying on these data our EP regularization.

5. References

1. P. Lobel, R. Kleinman, Ch. Pichot, L. Blanc-Féraud, and M. Barlaud, "Conjugate gradient method for solving inverse scattering with experimental data", *IEEE Antennas & Propagation Magazine*, **38**, no. 3, pp. 48-51, 1996.

2. P. Lobel, R. Kleinman, Ch. Pichot, L. Blanc-Féraud, and M. Barlaud, "Object Reconstruction from Far-Field Data Using Gradient and Gauss-Newton Type Methods", *in Digest USNC/URSI*, Newport Beach, USA, 1995, p. 233.

3. P. Lobel, L. Blanc-Féraud, Ch. Pichot, and M. Barlaud, "A new regularization scheme for inverse scattering", Research Note 95-72, Laboratoire Informatique, Signaux et Systèmes de Sophia Antipolis, 1995. Submitted to *Inverse Problems*.

4. P. Lobel, Ch. Pichot, L. Blanc-Féraud, and M. Barlaud, "Conjugate gradient algorithm with edge-preserving regularization for image reconstruction from experimental data", *in IEEE AP-S/URSI International Symposium*, Baltimore, USA, 1996, **1**, pp. 644-647.

5. P. Lobel, Ch. Pichot, L. Blanc-Féraud, and M. Barlaud, "Microwave Imaging : Reconstructions from Experimental Data using Conjugate Gradient and Enhancement by Edge-Preserving Regularization", to appear in the *International Journal of Imaging System and Technology*, Nov. 1996.

6. P. Charbonnier, L. Blanc-Féraud, G. Aubert, and M. Barlaud, "Deterministic Edge-Preserving Regularization in Computed Imaging", *IEEE Transactions on Image Processing*, **IP-5**, 12, 1996.

7. M. G. Coté, "Automated Swept-Angle Bistatic Scattering Measurements Using Continuous Wave Radar", *IEEE Transactions on Instrumentation and Measurement*, **IM-41**, 2, 1992, pp. 185-192.

8. J.B. Morris, D.A. Pommet, R.V. McGahan, and M.A. Fiddy, "Imaging of Strongly Scattering Targets from Real Data by Nonlinear Filtering", *in IEEE AP-S/URSI Digest*, Baltimore, USA, 1996, p. 80.